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(54) **APPARATUS AND METHODS FOR GENERATING ELECTROMAGNETIC RADIATION**

(75) Inventors: **Amar B. Kamdar**, Burnaby (CA); **David Malcolm Camm**, Vancouver (CA); **Mladen Bumbulovic**, Vancouver (CA); **Peter Lembesis**, Langley (CA)

(73) Assignee: **Mattson Technology, Inc.**, Fremont, CA (US)

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H01J 61/10	(2006.01)
H01J 61/52	(2006.01)
H01J 61/84	(2006.01)

(52) **U.S. Cl.**
CPC ***H01J 61/10*** (2013.01); ***H01J 61/52*** (2013.01); ***H01J 61/523*** (2013.01); ***H01J 61/84*** (2013.01)

(58) **Field of Classification Search**
CPC H01J 61/84; H01J 61/523; H01J 61/10; H01J 61/52
USPC 313/24, 35, 231.31, 231.41, 231.61
See application file for complete search history.

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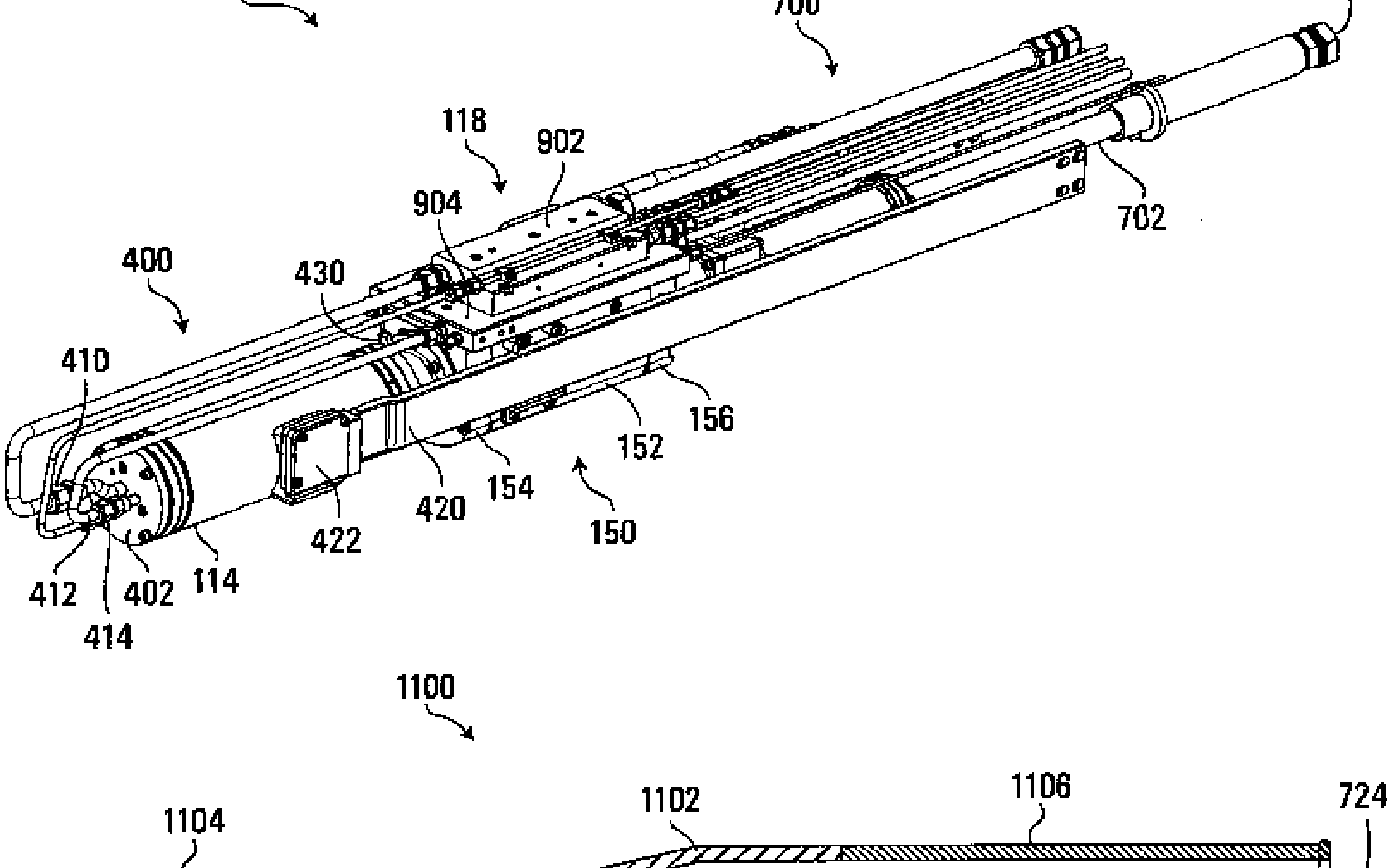
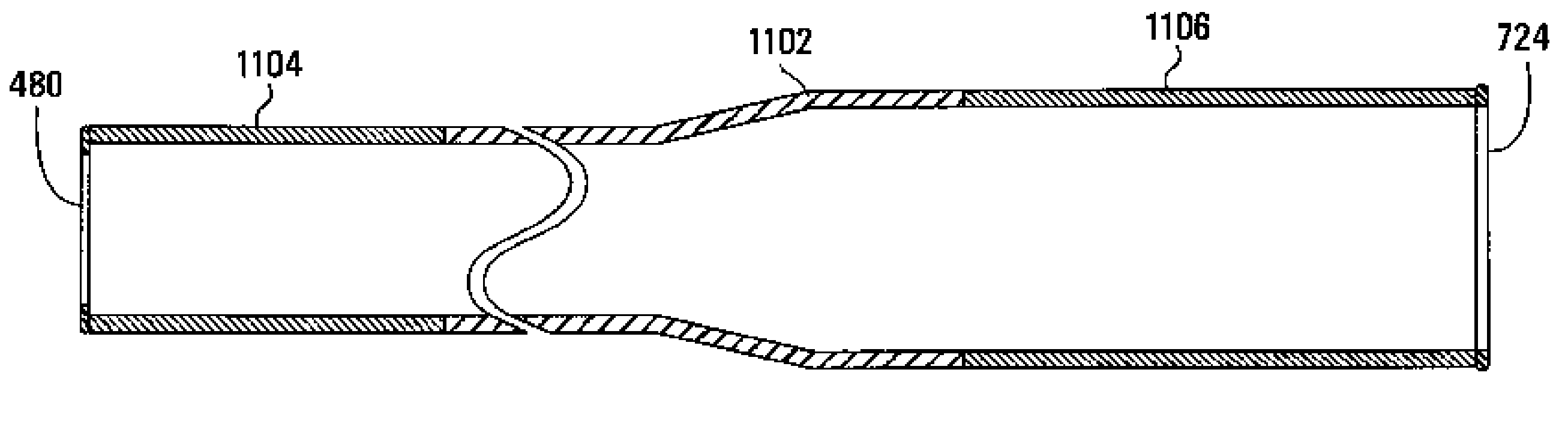
Primary Examiner — Vip Patel
(74) *Attorney, Agent, or Firm* — Knobbe, Martens, Olson & Bear, LLP

(57) **ABSTRACT**

An apparatus for generating electromagnetic radiation includes an envelope, a vortex generator configured to generate a vortexing flow of liquid along an inside surface of the envelope, first and second electrodes within the envelope configured to generate a plasma arc therebetween, and an insulative housing associated surrounding at least a portion of an electrical connection to one of the electrodes. The apparatus further includes a shielding system configured to block electromagnetic radiation emitted by the arc to prevent the electromagnetic radiation from striking all inner surfaces of the insulative housing. The apparatus further includes a cooling system configured to cool the shielding system.

37 Claims, 9 Drawing Sheets





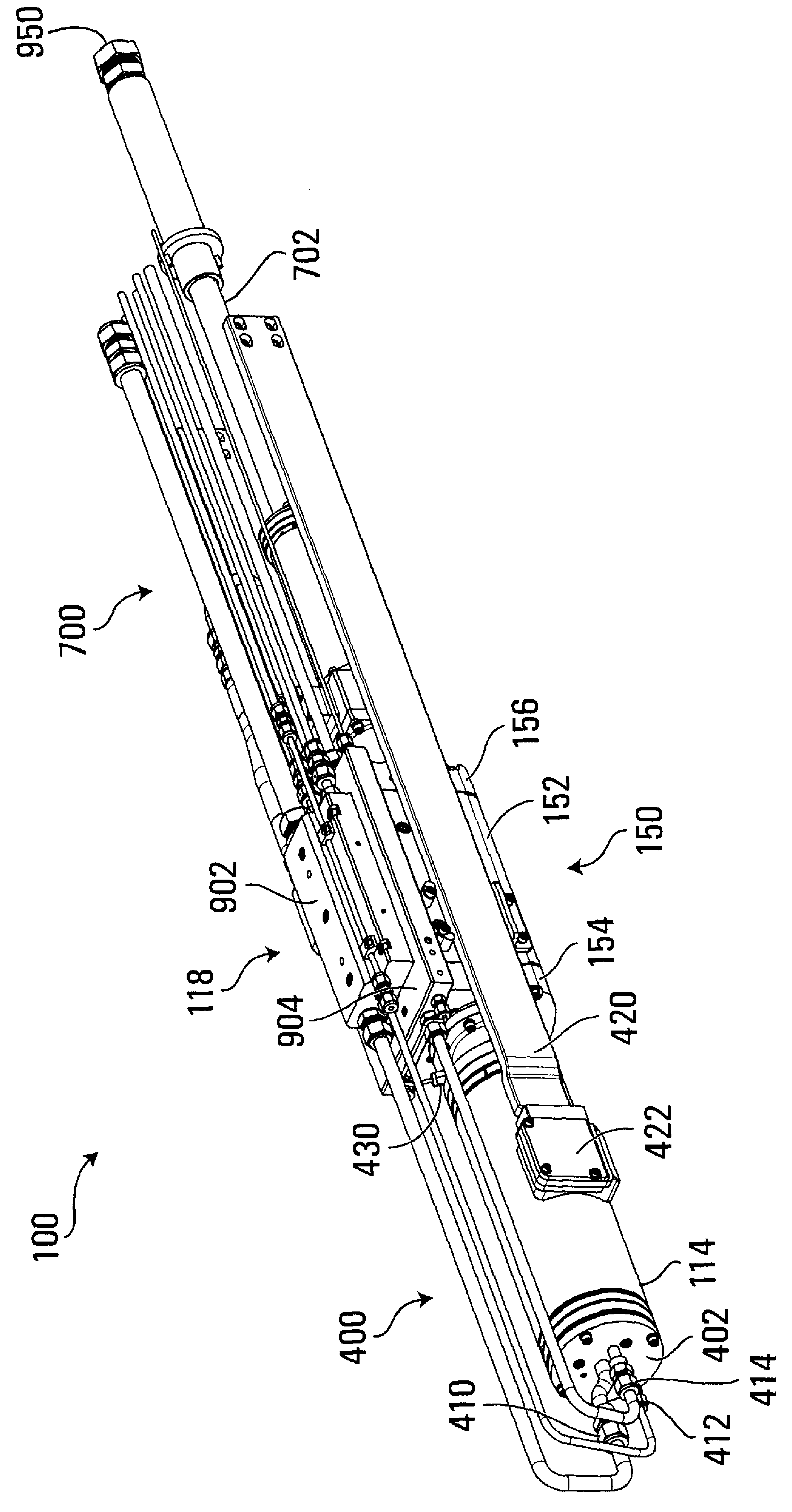

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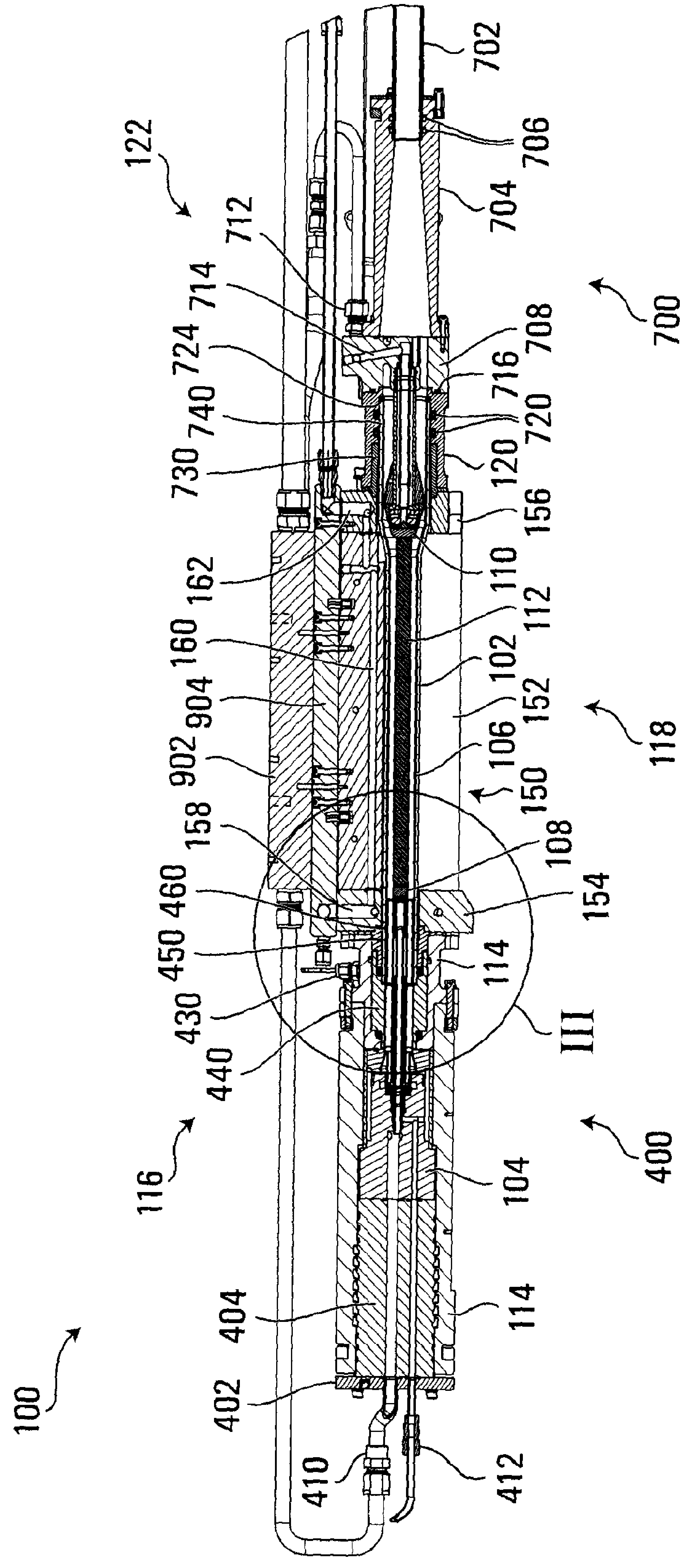
FIG. 1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902
152
106
118
158
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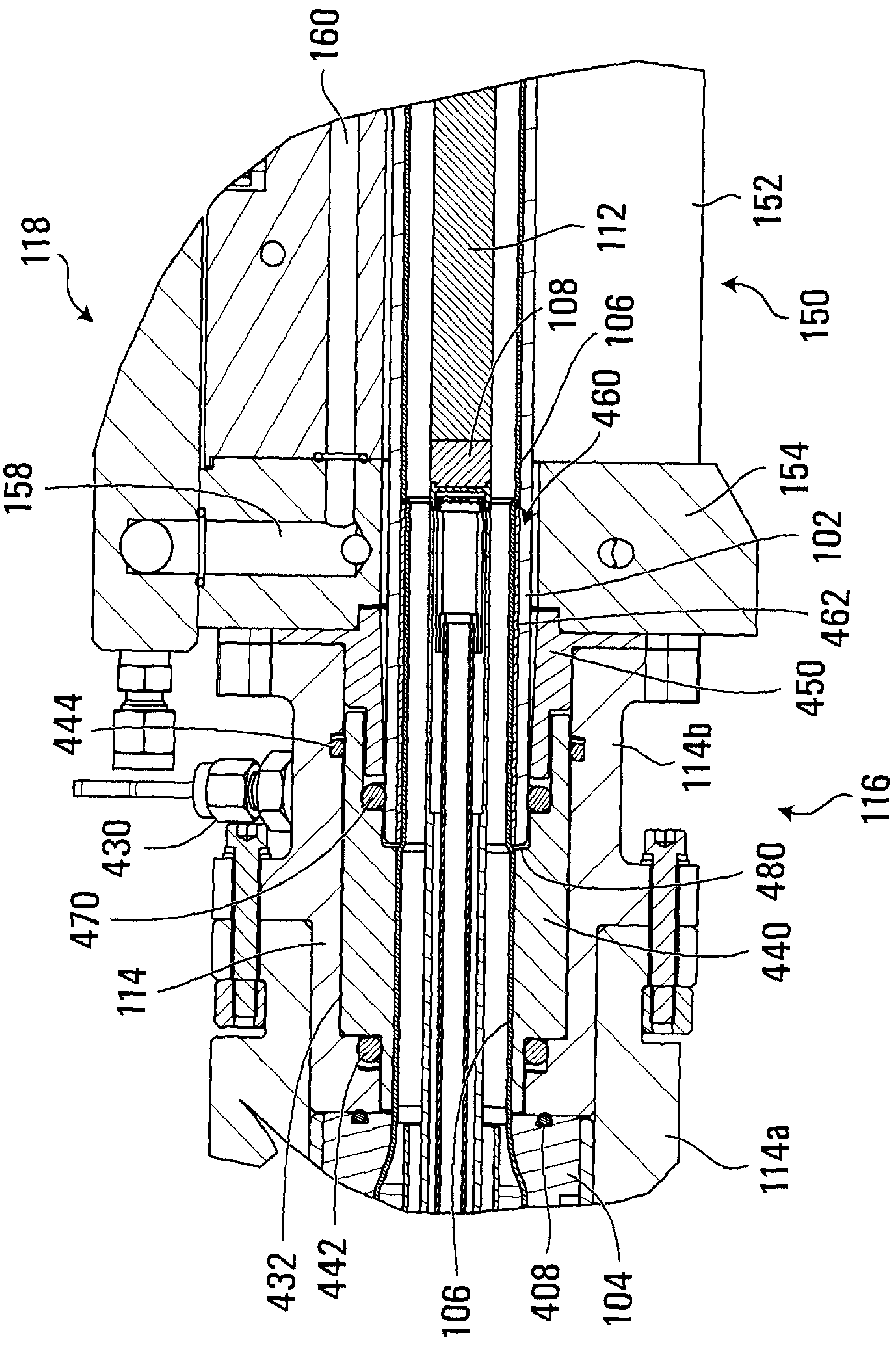
410
412

FIG. 2


118
160
158
112
152
108
106
150
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154
102
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116
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470
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440
114
114a
432
442
106
408
104

FIG. 3

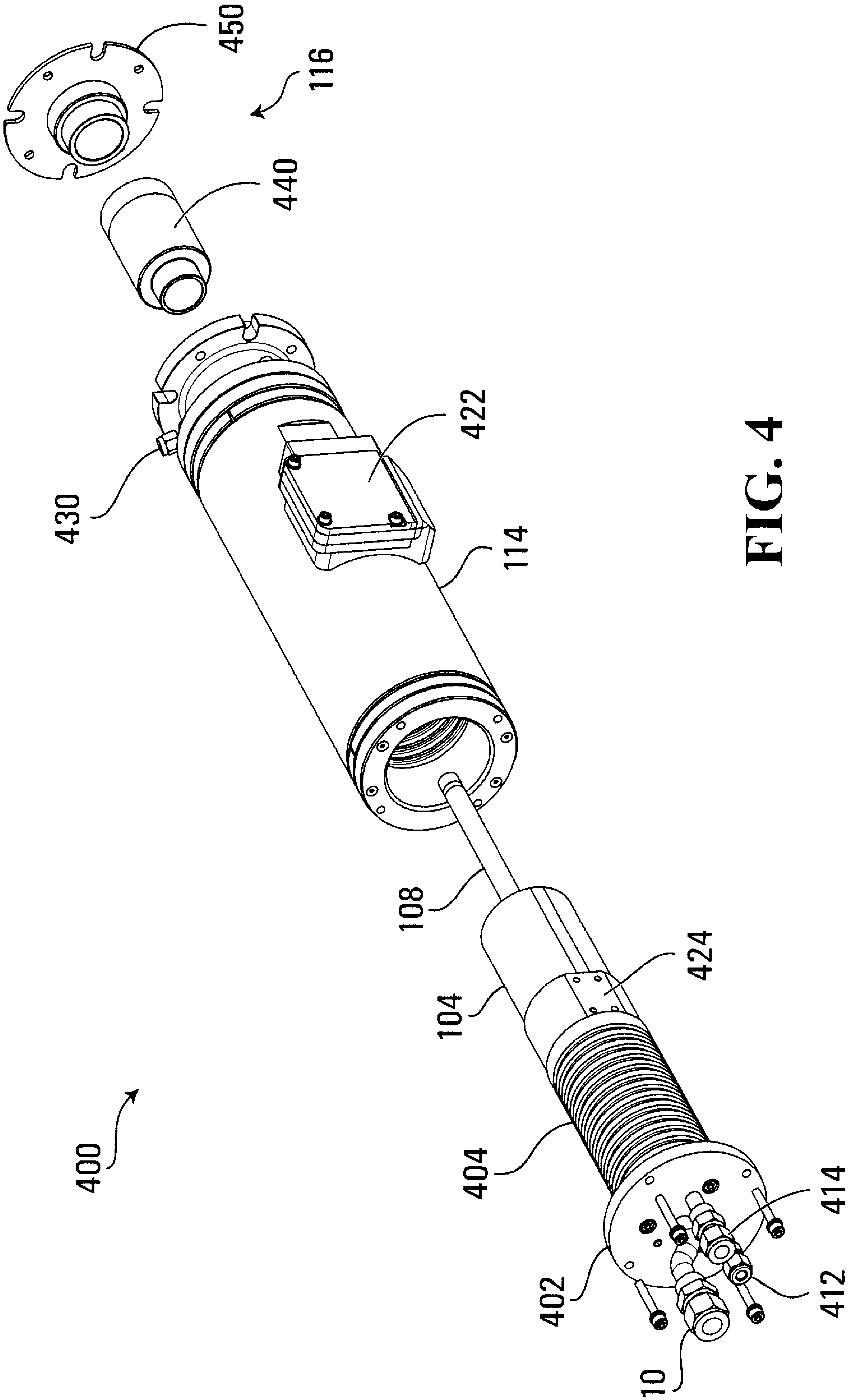

FIG. 4

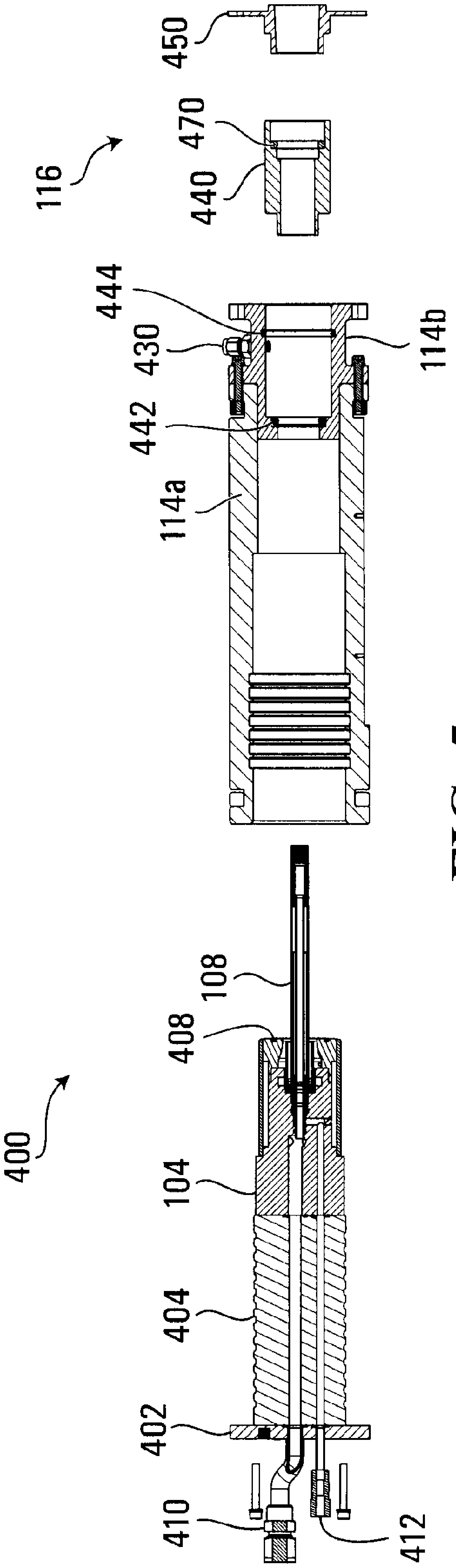
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FIG. 5

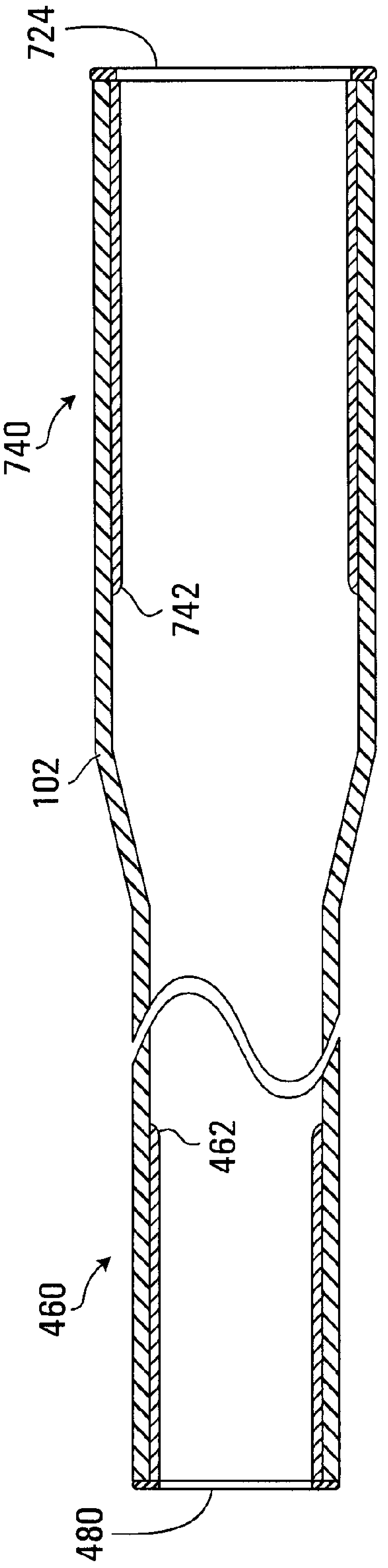
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FIG. 6

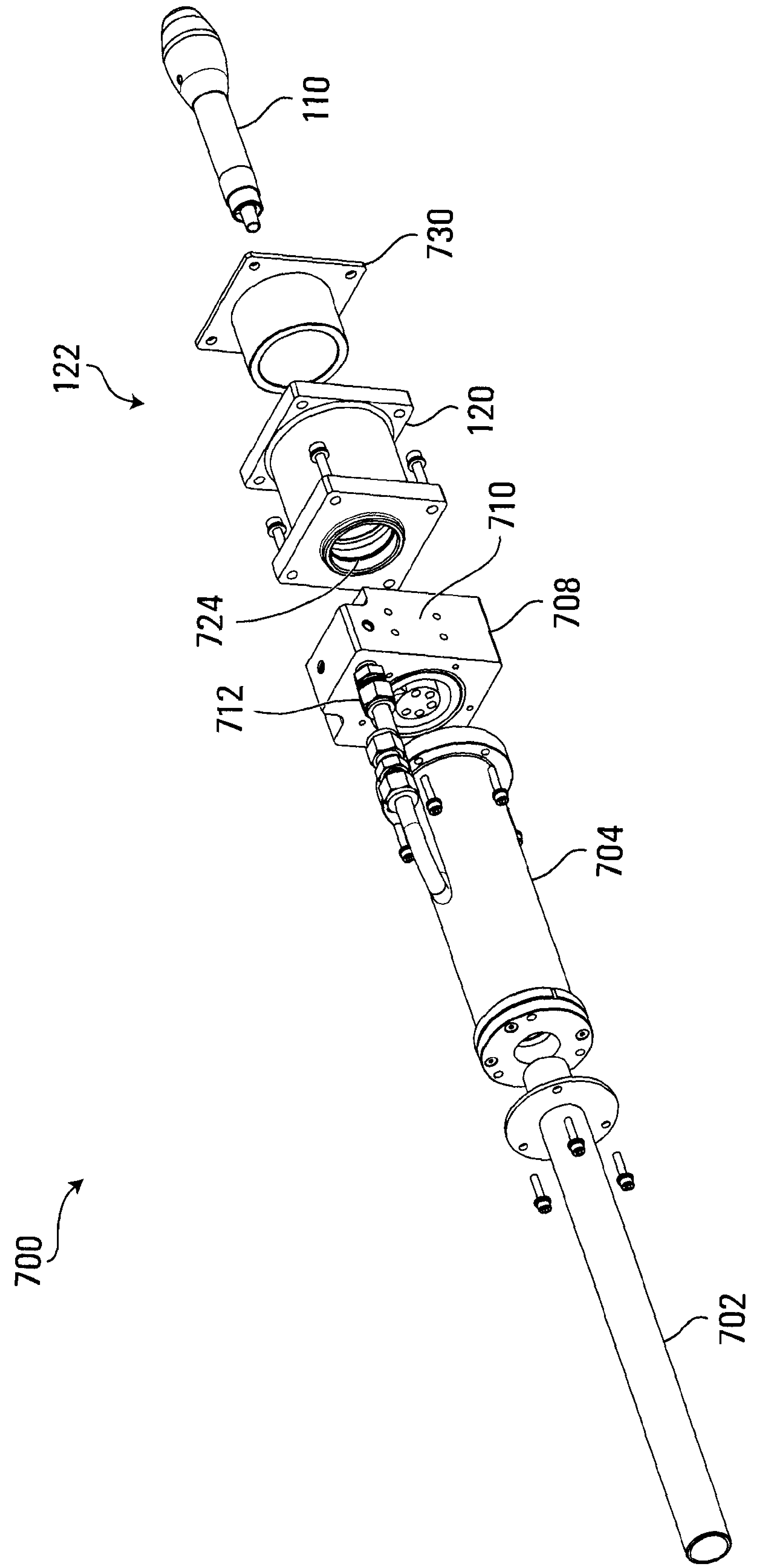

FIG. 7

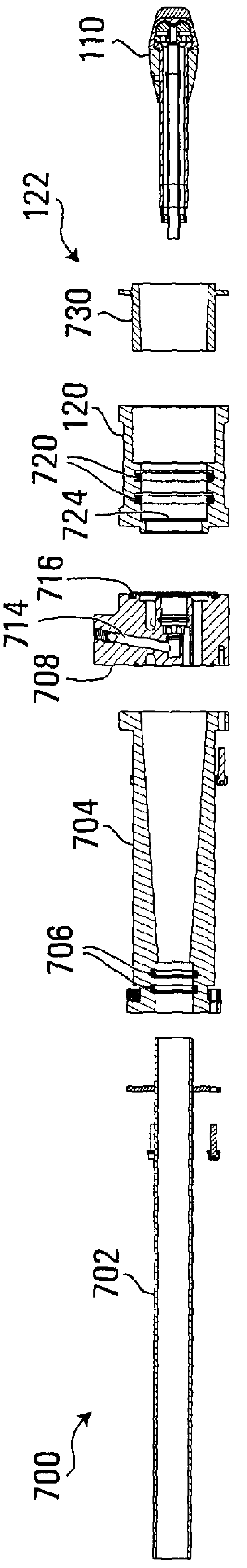

FIG. 8

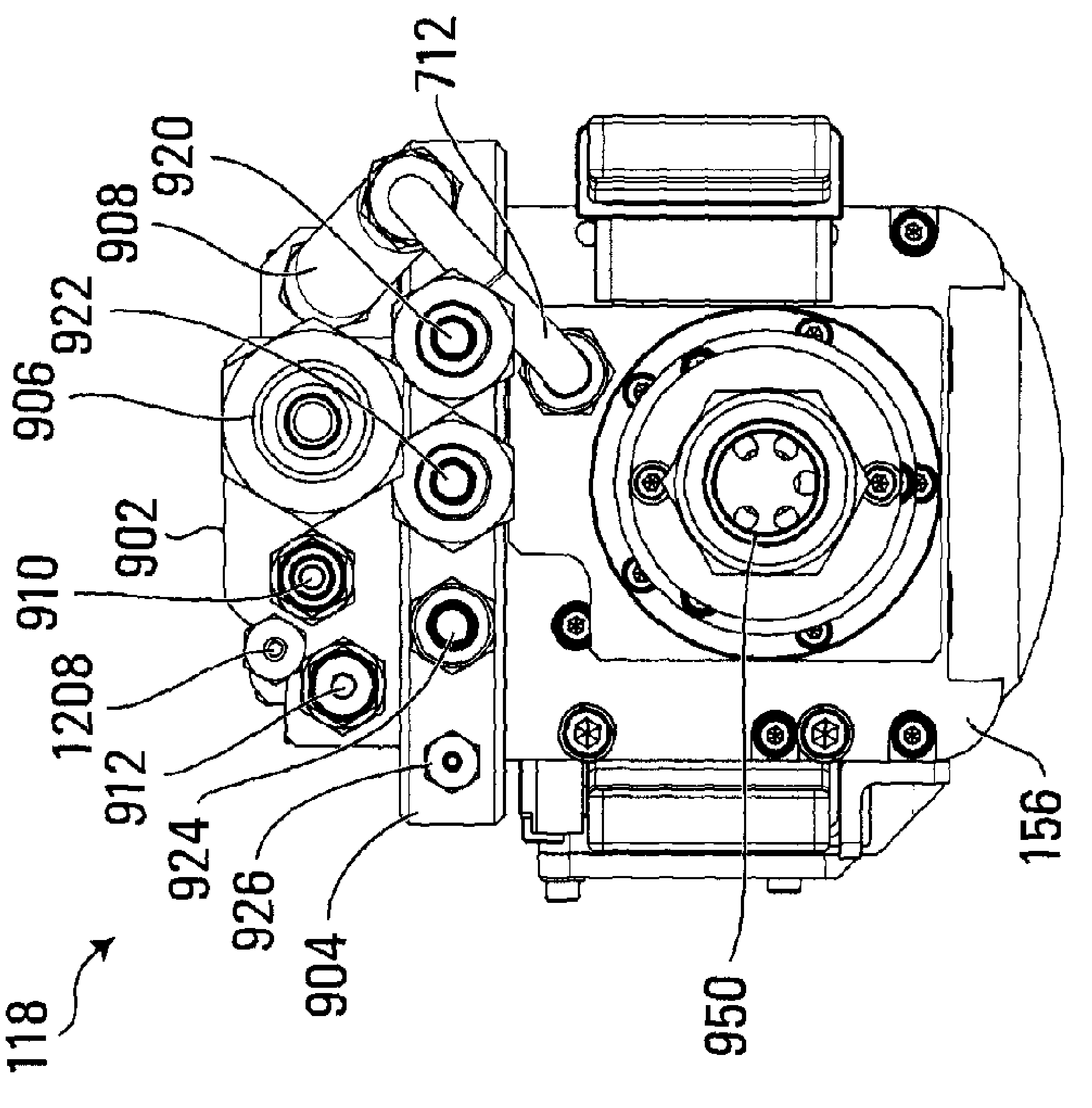

FIG. 9

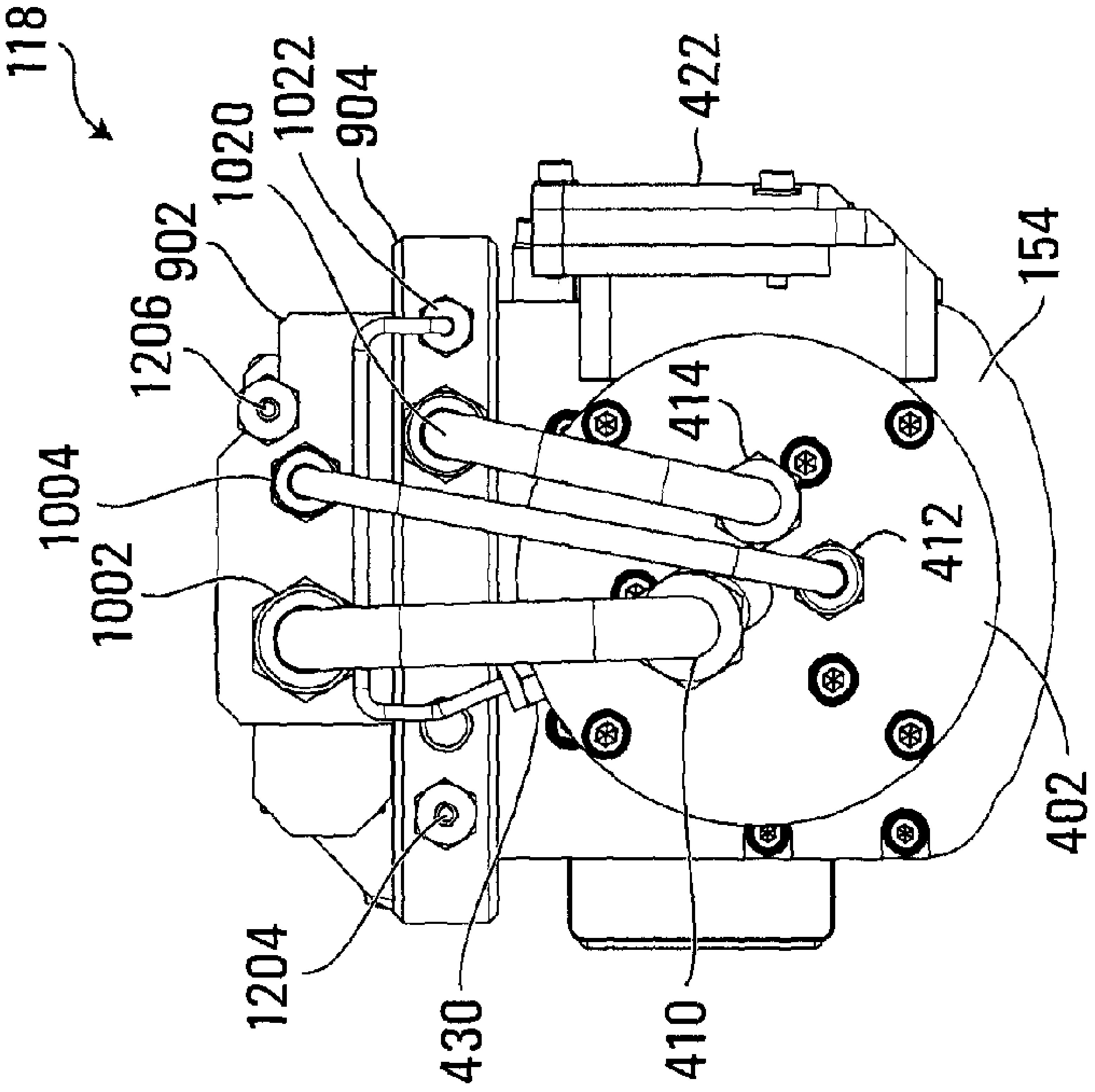

FIG. 10

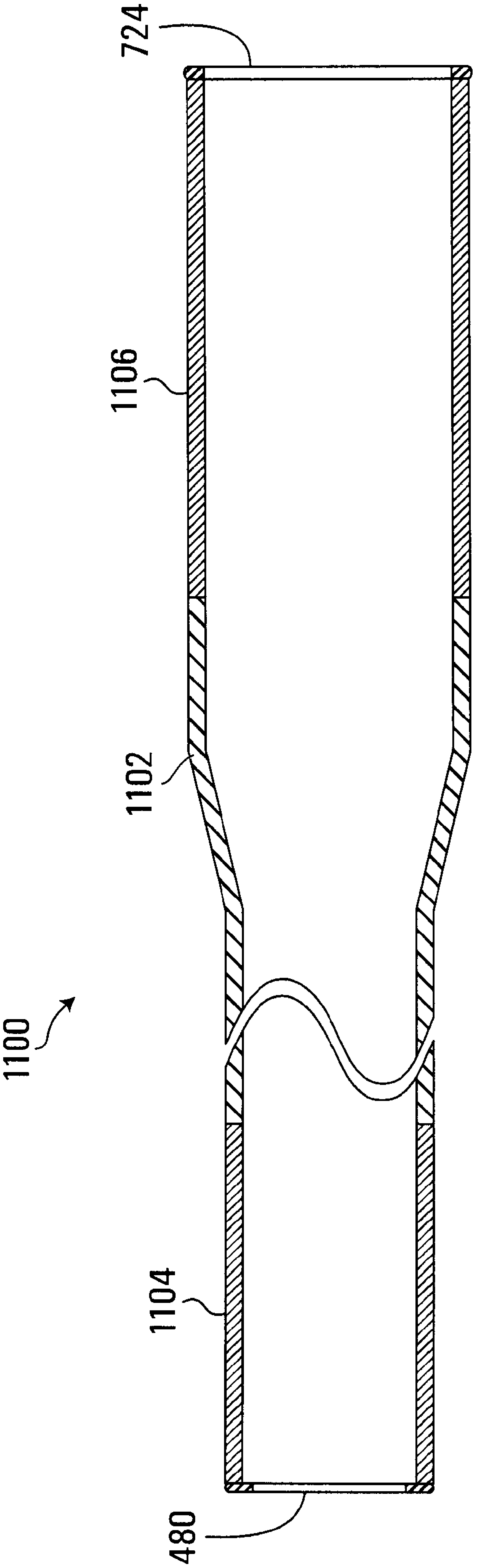

FIG. 11

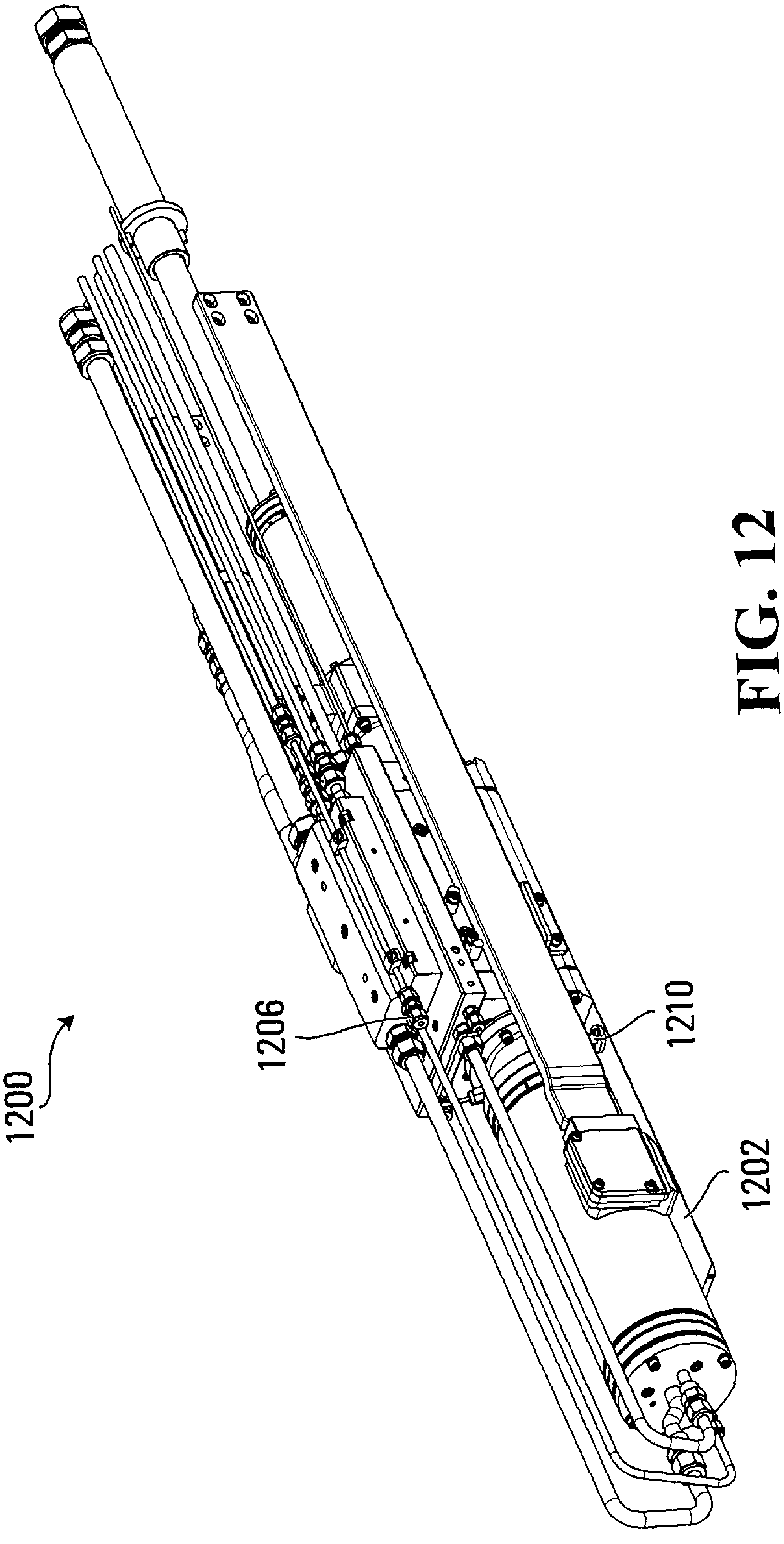

FIG. 12

APPARATUS AND METHODS FOR GENERATING ELECTROMAGNETIC RADIATION

BACKGROUND

1. Technical Field

The present invention relates to apparatus and methods for generating electromagnetic radiation. More particularly, illustrative embodiments relate to arc lamps having a vortexing flow of liquid along an inside surface of the arc tube or envelope.

2. Description of Related Art

Electric arc lamps are used to produce electromagnetic radiation for a wide variety of purposes. A typical conventional direct current (DC) arc lamp includes two electrodes, namely, a cathode and an anode, mounted within a quartz envelope often referred to as the arc tube. The envelope is filled with an inert gas such as xenon or argon. An electrical power supply is used to sustain a continuous plasma arc between the electrodes. Within the plasma arc, the plasma is heated by the high electrical current to a high temperature via particle collision, and emits electromagnetic radiation, at an intensity corresponding to the electrical current flowing between the electrodes.

The most powerful type of arc lamp is the so-called "water-wall" arc lamp, in which a liquid such as water is circulated through the arc chamber with a tangential velocity so as to form a vortexing liquid wall (the "water wall") flowing along the inside surface of the arc chamber envelope. The vortexing liquid wall cools the periphery of the inert gas column through which the arc is discharged. This cooling effect constricts the arc diameter and gives the arc a positive dynamic impedance. The rapid flow rate of the vortexing liquid wall ensures that this cooling effect is approximately constant over the entire length of the arc discharge, resulting in uniform arc conditions and spatially uniform emission of electromagnetic radiation. A vortexing flow of inert gas is maintained immediately radially inward from the vortexing liquid wall, to stabilize the arc. The vortexing liquid wall efficiently removes heat from the inside surface of the envelope and also absorbs infrared, thus lowering the amount of electromagnetic radiation absorbed by the envelope. The vortexing liquid wall also removes any material evaporated or sputtered by the electrodes, preventing darkening of the envelope. U.S. Pat. No. 4,027,185 to Nodwell et al., which shares overlapping inventorship with the present application, and which is incorporated herein by reference, is believed to disclose the first water-wall arc lamp. Further improvements upon such water-wall arc lamps are disclosed in U.S. Pat. No. 4,700,102 to Camm et al., U.S. Pat. No. 4,937,490 to Camm et al., U.S. Pat. No. 6,621,199 to Parfeniuk et al., U.S. Pat. No. 7,781,947 to Camm et al., and U.S. Patent Application Publication No. 2010/0276611 to Camm et al., all of which share overlapping inventorship with the present application, are commonly owned with the present application, and are incorporated herein by reference.

Due to the above-noted effects of the vortexing liquid wall, such water-wall arc lamps are capable of much higher power fluxes than other types of arc lamps. For example, the above-noted U.S. Pat. No. 4,027,185 to Nodwell et al. discloses and contemplates operation at 140 kilowatts, and subsequent water-wall arc lamps manufactured by the assignee of the present application have been rated for continuous operation at up to 500 kilowatts, and for pulsed or flashed operation at up to 6 megawatts. In contrast, other types of arc lamps are typically an entire order of magnitude less powerful, with continuous outputs typically limited to tens of kilowatts.

Many applications of such high-power water-wall arc lamps only require operation for short periods of time, such as several seconds. For example, in flash-assisted rapid thermal annealing of semiconductor wafers, as disclosed in commonly owned U.S. Pat. No. 6,941,063, an argon plasma water-wall arc lamp may be activated to continuously irradiate a semiconductor wafer for no more than several seconds, to heat the wafer in an approximately isothermal manner from room temperature to an intermediate temperature somewhere in the range between 600° C. and 1250° C., at a ramp rate between 250° C. per second and 400° C. per second. Upon reaching the intermediate temperature, another argon plasma water wall arc lamp is activated to produce an abrupt high-power irradiance flash, which may have a duration of about one millisecond for example, to heat the device side surface to a higher annealing temperature at a ramp rate in excess of 100,000° C. per second. Thus, in each annealing cycle, the water wall arc lamps may be activated for durations ranging from a millisecond to several seconds, with lengthy cooling periods between annealing cycles.

SUMMARY

The present inventors have investigated the continuous operation of water-wall arc lamps for longer periods of time in more challenging conditions than those that were involved in previous typical applications. Such conditions are not believed to have been previously encountered by any other type of arc lamp since other types of arc lamps are not capable of causing such conditions due to their significantly lower power outputs.

For example, the present inventors have investigated water-wall arc lamps as an alternative to laser or weld cladding heads for use in a cladding process, whereby various types of coatings are fused to metal structures. The metal structures may include steel pipes, tubes, plates or bars, or any other metal structures whose durability and lifetime are adversely affected by corrosion or wear. The coatings may include corrosion resistant alloys, wear-resistant alloys, cermet, ceramic or metal powders, for example. The coating is deposited onto the metal structure and the arc lamp then heat-treats the coating to metallurgically bond the coating to the metal structure.

Some such cladding applications, such as bonding a corrosion-resistant coating to the inside surface of a pipe, for example, pose particular challenges. For such a process, a water-wall arc lamp may be fitted with a specialized reflector to direct substantially all of the electromagnetic radiation emitted by the arc in a rectangular beam. The water-wall arc lamp is then inserted inside the pipe with the beam pointing downward, and the pipe is rotated about its central axis while the arc lamp is gradually moved forward along the central axis of the pipe, thereby scanning the beam along the entire inner surface of the pipe and metallurgically bonding the coating to the pipe. Advantageously, by operating the water-wall arc lamp at power levels of 100 to 500 kilowatts continuously for several hours at a time, the throughput can be increased significantly beyond conventional laser or weld cladding processes.

However, the present inventors have found that previous water-wall arc lamp designs may not be ideally suited for such conditions. Early designs such as the illustrative embodiments disclosed in the above-noted U.S. Pat. Nos. 4,027,185, 4,700,102 and 4,937,490 do not have insulative housings surrounding their conductive electrode assemblies and are therefore unsuitable for insertion into small diameter metal pipes, due to the likelihood of voltage breakdown causing an arc to inadvertently form between one of the conductive electrode assemblies and the pipe rather than between the two electrodes. Later designs such as the illustrative embodiments disclosed in the above-noted U.S. Pat. Nos. 6,621,199 and 7,781,947 have insulative housings surrounding their cathode assemblies, and their anodes may be grounded or maintained relatively close to ground potential, so that such lamps may be inserted into a grounded conductive pipe without risk of voltage breakdown and inadvertent arcing. However, illustrative embodiments of both of these later designs may permit a relatively small percentage of electromagnetic radiation from the arc to travel internally within the arc lamp and strike an inner surface of the insulative housing.

Although arc radiation incident on an inner surface of the insulative housing does not tend to be problematic for conventional conditions involving shorter duration operation at high power levels or longer duration operation at lower power levels, novel problems may begin to arise for sustained continuous operation at hundreds of kilowatts for long durations. For example, as disclosed in U.S. Pat. No. 7,781,947, the insulative housing surrounding the cathode assembly may be made of ULTEM™ plastic, which is an amorphous thermoplastic polyetherimide (PEI) resin with excellent heat resistance and dielectric properties permitting it to standoff high voltages. However, despite the formidable heat-resistant properties of the ULTEM™ plastic, sustained exposure to even a very small percentage of the electromagnetic radiation emitted by the arc when operating at enormous power levels of several hundred kilowatts for longer durations, ranging from minutes to several hours of continuous operation for some cladding applications, for example, may eventually cause overheating of the plastic and melting of the exposed surface. Moreover, the plastic tends to be at least partially transparent to some wavelengths emitted by the arc, with the result that arc radiation can be absorbed deeper within the plastic causing internal heating and melting, and can also travel through the plastic and irradiate adjacent metal components, causing the metal components to become sufficiently hot to melt the surface of the plastic adjacent to the metal.

Such overheating problems can be aggravated by the environmental conditions involved in some cladding applications. For example, if the arc lamp is inserted inside an 8-inch diameter pipe to metallurgically bond a coating to the inside surface of the pipe, the limited space and clearance within the pipe tend to diminish the ability of the lamp to dissipate heat into its ambient environment. Moreover, the lamp may be heated by its environment, as the heated pipe may emit infrared radiation and may also heat the lamp through conduction and convection through the ambient atmosphere.

The present inventors have found that merely placing an opaque shield such as a ceramic layer directly on the inner surface of the ULTEM™ plastic is not in itself sufficient to solve these problems, as the shield tends to be sufficiently heated by the arc radiation to melt the adjacent surface of the plastic. The present inventors have also found that merely replacing the ULTEM™ plastic with a ceramic insulative housing is not in itself a viable solution to these problems. Although ceramic material is opaque to the arc radiation and has much higher heat-resistance than the ULTEM™ plastic, heating the inner exposed surface causes large thermal gradients and stresses in the ceramic material which tend to crack the ceramic material, and such cracks are particularly problematic for ceramic materials due to their relatively low fracture toughness. Thermal expansion differences of the ceramic material and ULTEM™ plastic may create stresses in the plastic that leads to fracture. Moreover, ceramic materials may be too brittle to bear the mechanical stresses that the insulative housing is expected to endure for some applications.

In accordance with an illustrative embodiment of the present disclosure, an apparatus for generating electromagnetic radiation includes an envelope, a vortex generator configured to generate a vortexing flow of liquid along an inside surface of the envelope, first and second electrodes within the envelope configured to generate a plasma arc therebetween, and an insulative housing associated surrounding at least a portion of an electrical connection to one of the electrodes. The apparatus further includes a shielding system configured to block electromagnetic radiation emitted by the arc to prevent the electromagnetic radiation from striking all inner surfaces of the insulative housing. The apparatus further includes a cooling system configured to cool the shielding system.

Advantageously, in such an embodiment, the shielding system prevents electromagnetic radiation emitted by the arc from striking the inner surfaces of the insulative housing, thereby preventing overheating and melting of the insulative housing by direct irradiance. Likewise, the shielding system also prevents internal arc radiation from travelling through the insulative housing and striking other adjacent components of the arc lamp, thereby preventing such other adjacent components from overheating and melting the adjacent surface of the insulative housing. By cooling the shielding system, overheating of the shielding system is avoided, thereby advantageously preventing components of the shielding system from overheating and melting adjacent surfaces of the insulative housing.

In accordance with another illustrative embodiment, an apparatus for generating electromagnetic radiation includes means for generating a vortexing flow of liquid along an inside surface of an envelope, and means for generating a plasma arc between first and second electrodes within the envelope. The apparatus further includes means for blocking electromagnetic radiation emitted by the arc to prevent the electromagnetic radiation from striking all inner surfaces of an insulative housing surrounding at least a portion of an electrical connection to one of the electrodes. The apparatus further includes means for cooling the means for blocking.

In accordance with another illustrative embodiment, a method of generating electromagnetic radiation includes generating a vortexing flow of liquid along an inside surface of an envelope, and generating a plasma arc between first and second electrodes within the envelope. The method further includes blocking electromagnetic radiation emitted by the arc with a shielding system to prevent the electromagnetic radiation from striking all inner surfaces of an insulative housing surrounding at least a portion of an electrical connection to one of the electrodes. The method further includes cooling the shielding system.

Blocking may include blocking the electromagnetic radiation with an opaque surface of an insulative shielding component of the shielding system. The insulative shielding component may include a ceramic shielding component.

Cooling may include exposing the opaque surface of the insulative shielding component to the vortexing flow of liquid.

Alternatively, or in addition, blocking may include blocking the electromagnetic radiation with an opaque portion of the envelope. The opaque portion of the envelope may include a portion of the envelope having an opaque coating on an inside surface thereof. Alternatively, the opaque portion of the envelope may be composed of opaque quartz. Cooling may include exposing the opaque portion of the envelope to the vortexing flow of liquid.

Alternatively, or in addition, blocking may include blocking the electromagnetic radiation with an opaque surface of a conductive shielding component of the shielding system. Cooling may include conductively cooling the conductive shielding component. Conductively cooling may include conducting heat energy between the conductive shielding component and a liquid cooled conductor.

Thus, in some embodiments, blocking may include blocking the electromagnetic radiation with an opaque surface of an insulative shielding component of the shielding system, an opaque portion of the envelope and an opaque surface of a conductive shielding component of the shielding system.

Blocking further may include blocking the electromagnetic radiation from striking an O-ring seal.

The method may further include sealing at least one component against the envelope with a heat-resistant O-ring seal.

The method may further include blocking the electromagnetic radiation emitted by the arc with a second shielding system to prevent the electromagnetic radiation from striking all inner surfaces of a second insulative housing surrounding at least a portion of the other one of the electrodes, and cooling the second shielding system.

Blocking may include blocking the electromagnetic radiation with a light-piping shielding component of the shielding system to prevent the electromagnetic radiation from axially exiting from an annular interior volume of the envelope. The light-piping shielding component may include an opaque washer abutting a distal end of the envelope. Cooling may include exposing the washer to the vortexing flow of liquid.

The method may further include heat-shielding at least some of an outer surface of the insulative housing with an external heat shield, and cooling the external heat shield.

Other aspects and features of illustrative embodiments will become apparent to those ordinarily skilled in the art upon review of the following description of such embodiments in conjunction with the accompanying figures.

BRIEF DESCRIPTION OF THE DRAWINGS

In drawings which illustrate embodiments of the present disclosure,

FIG. **1** is an isometric view of an apparatus for generating electromagnetic radiation according to a first embodiment;

FIG. **2** is a section view of the apparatus of FIG. **1**;

FIG. **3** is a detail section view of a portion of the apparatus of FIG. **1**;

FIG. **4** is an exploded isometric view of a cathode assembly of the apparatus of FIG. **1**;

FIG. **5** is an exploded section view of the cathode assembly shown in FIG. **4**;

FIG. **6** is a segmented section view of an envelope of the apparatus of FIG. **1**;

FIG. **7** is an exploded isometric view of an anode assembly of the apparatus of FIG. **1**;

FIG. **8** is an exploded section view of the anode assembly shown in FIG. **6**;

FIG. **9** is an anode side elevation view of the apparatus of FIG. **1**;

FIG. **10** is a cathode side elevation view of the apparatus of FIG. **1**;

FIG. **11** is a segmented section view of an envelope of an apparatus for generating electromagnetic radiation according to a second embodiment; and

FIG. **12** is an isometric view of an apparatus for generating electromagnetic radiation according to a third embodiment.

DETAILED DESCRIPTION

Referring to FIGS. **1**, **2** and **3**, an apparatus for generating electromagnetic radiation according to a first embodiment of the disclosure is shown generally at **100** in FIG. **2**. In this embodiment, the apparatus **100** includes an envelope **102**, and a vortex generator **104** configured to generate a vortexing flow of liquid **106** along an inside surface of the envelope **102**. In this embodiment, the apparatus **100** further includes first and second electrodes **108** and **110** within the envelope **102** configured to generate a plasma arc **112** therebetween.

In the present embodiment, the apparatus **100** further includes an insulative housing **114** surrounding at least a portion of an electrical connection to one of the electrodes, which in this embodiment is the first electrode **108**, and a shielding system shown generally at **116**, configured to block electromagnetic radiation emitted by the arc **112** to prevent the electromagnetic radiation from striking all inner surfaces of the insulative housing **114**. In this embodiment, the apparatus **100** further includes a cooling system shown generally at **118**, configured to cool the shielding system **116**.

In this embodiment, the apparatus further includes a second insulative housing **120** surrounding at least a portion of the other one of the electrodes, which in this embodiment is the second electrode **110**, and a second shielding system **122** configured to block the electromagnetic radiation emitted by the arc to prevent the electromagnetic radiation from striking all inner surfaces of the second insulative housing. Also in this embodiment, the cooling system **118** is configured to cool the second shielding system **122**.

The first and second shielding systems **116** and **122** and the cooling system **118** are described in greater detail below.

Generally, apart from the first and second shielding systems **116** and **122** and the complementary aspects of the cooling system **118** described in greater detail below, the apparatus **100** is similar to that described in the above-noted commonly owned U.S. Pat. No. 7,781,947. Accordingly, to avoid unnecessary repetition, numerous details of ancillary features of the present embodiment are omitted from the present disclosure.

Cathode Assembly and Cathode Side Shielding System

Referring to FIGS. **1**, **2**, **3**, **4** and **5**, in this embodiment the apparatus **100** includes a cathode assembly shown generally at **400** in FIGS. **4** and **5**. In this embodiment, the cathode assembly **400** includes a cathode supply plate **402** connected to a cathode isolation spacer **404**, which in turn is connected to the vortex generator **104**, which in turn is connected to the first electrode **108**, which in this embodiment acts as a cathode.

In this embodiment, the cathode supply plate **402** includes a liquid coolant inlet port **410**, a liquid coolant outlet port **412** and an inert gas supply inlet port **414**. In the present embodiment, the liquid coolant inlet port **410** receives a pressurized supply of liquid coolant, which in this embodiment is deionized water, and supplies the liquid coolant to the vortex generator **104** and to the first electrode **108**. Also in this embodiment, the liquid coolant outlet port **412** exhausts liquid coolant that has circulated through the interior of the first electrode **108**. The circulation of the liquid coolant through the first electrode **108** is described in greater detail in the above-noted commonly owned U.S. Pat. No. 7,781,947, and therefore, further details are omitted herein. Finally, in this embodiment the inert gas supply inlet port **414** receives a pressurized supply of inert gas, which in this embodiment is argon, and supplies it to the vortex generator **104**.

In this embodiment, the vortex generator **104** receives the pressurized supply of liquid coolant, which is then channeled through a plurality of internal holes within the vortex generator which exhaust the pressurized liquid into the envelope **102**. More particularly, as the liquid is forced through the holes in the vortex generator, it acquires a velocity with components not only in the radial and axial directions relative to the envelope **102**, but also a velocity component tangential to the circumference of the inside surface of the envelope **102**. Thus, as the pressurized liquid exits the vortex generator **104** and enters the envelope **102**, the liquid forms the vortexing flow of liquid **106** (also referred to as a "water wall") circling around the inside surface of the envelope **102** as it traverses the envelope in the axial direction toward the second electrode **110**. Similarly, in this embodiment the vortex generator **104** also receives the pressurized supply of inert gas, which is channeled through a plurality of holes within the vortex generator **104** and is then exhausted into the envelope **102** slightly radially inward from the vortexing flow of liquid **106**, so that the exiting gas also has velocity components not only in the radial and axial directions but also tangential to the inside surface of the water wall. Thus, as the pressurized gas is forced out of the vortex generator **104** and into the envelope **102**, it forms a vortexing gas flow immediately radially inward from the vortexing flow of liquid **106**, circling around in the same rotational direction as the vortexing flow of liquid **106**. The structure of the vortex generator **104** and the holes therein to generate the vortexing flow of liquid **106** and the vortexing flow of gas contained therein are described in the above-noted commonly owned U.S. Pat. No. 7,781,947, and therefore, further details are omitted herein.

In this embodiment, the vortex generator **104** is an electrical conductor. More particularly, in this embodiment the vortex generator **104** is composed of brass, and forms a portion of the electrical connection to the first electrode **108**, which in this embodiment acts as the cathode. More particularly, in this embodiment the electrical connection to the first electrode **108** includes an insulated electrical busbar **420** shown in FIG. **1**, which is connected to an electrical connection surface **424** of the vortex generator **104** shown in FIG. **4**, through an insulated bus connector **422** shown in FIGS. **1** and **4** which extends through the insulative housing **114**. In this embodiment, the insulated bus connector **422** has a connection port which points toward the anode side of the apparatus **100**, which facilitates a compact electrical connection with minimal outward radial protrusion. Thus, the insulated electrical busbar **420**, the insulated bus connector **422** and the vortex generator **104** all form part of the electrical connection to the cathode.

Accordingly, during operation, the vortex generator **104** is at the same electrical potential as the first electrode **108**. In this embodiment, the other end of the insulated electrical busbar **420** is connected with an electrical cable (not shown) to the negative voltage terminal of a power supply (not shown) for the apparatus **100**, thereby connecting the first electrode **108** and the vortex generator **104** to the negative terminal of the power supply. The power supply may include a power supply similar to that disclosed in the above-noted U.S. Pat. No. 7,781,947, for example, optionally omitting components not required for the continuous operation of the present embodiment such as the dedicated capacitor banks for flash-lamp operation, for example. Alternatively, other suitable power supplies may be substituted. Thus, in this embodiment, the vortex generator **104** is at the same voltage as the negative terminal of the power supply and the cathode, which in this embodiment may include voltages as high as about −30 kilovolts at startup, and voltages up to −300 volts when running, relative to ground.

In this embodiment, the cathode isolation spacer **404** acts as a high-voltage standoff insulator, between the vortex generator **104** and the cathode supply plate **402**, to prevent voltage breakdown and inadvertent arcing between the vortex generator **104** and the cathode supply plate **402**. More particularly, in this embodiment the cathode isolation spacer **404** is composed of a thermoplastic, which in this embodiment is white DELRIN™ polyoxymethylene (POM).

Likewise, since the vortex generator **104** forms a portion of the electrical connection to the first electrode **108**, in this embodiment the insulative housing **114** surrounds the vortex generator **104**, and thus acts as a standoff insulative housing to prevent inadvertent voltage breakdown or arcing between the vortex generator **104** and any conductive objects in proximity to the apparatus **100**. Indeed, in this embodiment the insulative housing **114** surrounds the entire vortex generator **104** and most of the first electrode **108**. To the extent that the insulative housing **114** does not surround the axially innermost tip of the first electrode **108**, the insulative housing **114** and the envelope **102** overlap in the axial direction, so that this innermost portion of the first electrode **108** is surrounded by the envelope **102**. Thus, the entire high-voltage subassembly of the vortex generator **104** and the first electrode **108** is surrounded by the overlapping combination of the envelope **102** and the insulative housing **114**. In this embodiment, the envelope **102** is composed of quartz, as discussed in greater detail below. Also in this embodiment, the insulative housing **114** is composed of an amorphous thermoplastic polyetherimide (PEI) resin, namely, ULTEM™ plastic, manufactured by SABIC (formerly by General Electric Plastics Division).

In this embodiment, the insulative housing **114** is fabricated from two separate pieces of ULTEM™, an axially outermost piece **114***a* and an axially innermost piece **114***b*, which are glued and bolted together, as shown in FIGS. **2**, **3** and **5**. When assembled, the vortex generator **104** is surrounded entirely by the axially outermost piece **114***a* of the insulative housing **114**, and an axially inward-facing surface of the vortex generator **104** is sealed against an axially outward-facing surface of the axially innermost piece **114***b* of the insulative housing **114** with an O-ring **408**, which in this embodiment is composed of silicone.

Referring to FIGS. **3**-**5**, in this embodiment the insulative housing **114** further includes an insulative gas supply inlet port **430** for receiving pressurized insulative gas, which in this embodiment is nitrogen. The pressurized nitrogen fills a thin gap **432** shown in FIG. **3**, defined between a radially inward-facing surface of the axially innermost piece of the two-piece insulative housing **114** and a radially outward-facing surface of an insulative shielding component **440** discussed below. The thin gap **432** is sealed by two O-rings **442** and **444**, which in this embodiment are composed of silicone. The pressurized nitrogen gap increases the effective high voltage creepage distance, thereby enhancing the ability of the insulative housing **114** to standoff the high voltage of the first electrode **108** and prevent inadvertent voltage breakdown or arcing between the first electrode and conductive objects other than the second electrode **110** (notably including a copper conductive shielding component of the shielding system discussed below, but more generally including any other conductive objects in proximity to the electrode, whether internal or external to the apparatus **100**).

Referring to FIGS. **2**, **3**, **4**, **5** and **6**, in this embodiment the cathode assembly **400** includes various components of the shielding system **116**. In this embodiment, the shielding system **116** includes the insulative shielding component **440**, which in this embodiment has an opaque surface configured to block electromagnetic radiation emitted by the plasma arc **112**. More particularly, in this embodiment the insulative shielding component **440** is a ceramic shielding component, composed of opaque ceramic material, and therefore all of its surfaces are opaque. More particularly still, in this embodiment the insulative shielding component **440** is composed of MACOR™ machinable glass ceramic, manufactured by Corning.

Also in this embodiment, the shielding system **116** includes a conductive shielding component **450**, which in this embodiment also has an opaque surface configured to block electromagnetic radiation emitted by the plasma arc **112**. More particularly, in this embodiment the conductive shielding component **450** is composed of machined copper, and therefore, all of its surfaces are opaque.

Referring to FIGS. **2**, **3** and **6**, in this embodiment the shielding system **116** includes an opaque portion **460** of the envelope **102** configured to block electromagnetic radiation emitted by the plasma arc **112**. More particularly, in this embodiment the opaque portion **460** of the envelope **102** includes a portion of the envelope having an opaque coating **462** on an inside surface thereof. More particularly still, in this embodiment the envelope **102** is composed of HSQ **300** grade electrically fused quartz manufactured by Heraeus, and the opaque coating **462** is an HRC™ Heraeus Reflective Coating, which consists of a pure silica material having an open porous microstructure providing diffusive (near-Lambertian) reflectivity over a broad spectral range from ultraviolet to infrared, with high thermal stability. In this embodiment, the opaque coating **462** is applied over the axially outermost 70 mm of the inner surface of the envelope **102** at the cathode side. In this embodiment, the envelope **102** has a thickness of about 2.5 mm at the cathode side, and the opaque coating has a thickness of about 0.5 to 1 mm.

Thus, as shown in FIG. **3**, the shielding system **116**, or more particularly, the opaque surface of the insulative shielding component **440**, the opaque portion **460** of the envelope **102** and the opaque surface of the conductive shielding component **450**, block the electromagnetic radiation emitted by the arc **112** from striking all inner surfaces of the insulative housing **114**.

Referring to FIGS. **3**, **5** and **6**, in this embodiment, the shielding system **116** is further configured to block the electromagnetic radiation emitted by the arc from striking an O-ring seal. In this regard, in the present embodiment, the cathode assembly **400** further includes a heat-resistant O-ring seal **470** configured to seal at least one component of the apparatus **100** against the envelope **102**. More particularly, in this embodiment the heat-resistant O-ring seal **470** seals an outer surface of the opaque portion **460** of the envelope **102** against an inner surface of the insulative shielding component **440** of the shielding system **116**. In this embodiment, the heat-resistant O-ring seal **470** is a KALREZ™ perfluoroelastomer O-ring seal manufactured by DuPont, and has greater heat resistance than the silicone O-rings **408**, **442** and **444** used elsewhere in the cathode assembly **400**. In this embodiment, the opaque portion **460** of the envelope **102**, or more particularly the opaque coating **462**, blocks electromagnetic radiation emitted by the plasma arc **112** from striking the heat-resistant O-ring seal **470**.

Advantageously, since the opaque coating **462** is applied to the inside rather than the outside surface of the envelope **102**, the opaque coating **462** does not interfere with the ability of the heat-resistant O-ring seal **470** to seal between the envelope **102** and the insulative shielding component **440**.

Also in this embodiment, as shown in FIGS. **3** and **6**, the shielding system **116** further includes a light-piping shielding component **480** configured to prevent electromagnetic radiation from axially exiting from an annular interior volume of the envelope. In this embodiment, the light-piping shielding component includes an opaque washer. More particular, in this embodiment the opaque washer includes a white reflective Teflon™ spacer interposed between an axially outward-facing cathode side end of the envelope **102** and an axially inward-facing abutment of the insulative shielding component **440**. Alternatively, the light-piping shielding component **480** may be omitted.

In this embodiment the above-mentioned components of the shielding system **116**, namely, the opaque surface of the insulative shielding component **440**, the opaque portion **460** of the envelope **102**, the opaque surface of the conductive shielding component **450** and the light-piping shielding component **480**, are advantageously cooled by the cooling system **118**, as discussed in greater detail below following a summary of the anode assembly and anode side shielding system.

Anode Assembly and Anode Side Shielding System

Referring to FIGS. **2**, **7** and **8**, in addition to shielding the insulative housing **114** at the cathode side of the apparatus **100** from arc radiation, in this embodiment similar shielding is provided at the anode side of the apparatus **100**. Thus, as noted earlier herein, in this embodiment the apparatus **100** further includes the second insulative housing **120** surrounding at least a portion of the other one of the electrodes, which in this embodiment is the second electrode **110**, which is configured to act as the anode. In this embodiment, the apparatus **100** further includes the second shielding system **122** configured to block the electromagnetic radiation emitted by the arc to prevent the electromagnetic radiation from striking all inner surfaces of the second insulative housing **120**. Also in this embodiment, the cooling system **118** is configured to cool the second shielding system **122**.

Referring to FIGS. **2**, **7** and **8**, in this embodiment an anode assembly of the apparatus **100** is shown generally at **700**. In this embodiment, the anode assembly **700** includes a liquid and gas exhaust tube **702** and an exhaust chamber **704**, through which the vortexing flow of liquid **106** and the vortexing flow of inert gas are exhausted from the apparatus **100**. In this embodiment, the liquid and gas exhaust tube **702** is composed of stainless steel, and the exhaust chamber **704** is an insulative housing composed of high performance plastic, which in this embodiment is ULTEM™ plastic. In this embodiment, an axially innermost end of the liquid and gas exhaust tube **702** is inserted into and sealed against an axially outermost end of the exhaust chamber **704** by two O-rings **706** shown in FIG. **8**, which in this embodiment are ethylene propylene diene monomer (EPDM) O-rings.

Referring to FIGS. **1**, **2**, **7** and **8**, in this embodiment, the anode assembly **700** further includes an electrode housing **708**, attached to and in electrical communication with the second electrode **110**. In the present embodiment, the electrode housing **708** is a conductive housing composed of brass, and includes an electrical connection surface **710**. In this embodiment, an insulated electrical busbar (not shown but similar to the busbar **420** shown in FIG. **1**) is connected to the electrical connection surface **710** through an insulated bus connector (not shown but similar to the connector **422** shown in FIG. **1**, and also having a connection port pointing toward the anode side of the apparatus **100** to facilitate compact electrical connection with minimal radial protrusion). The other end of the insulated electrical busbar is connected with an electrical cable (not shown) to a positive voltage terminal of the power supply (not shown) for the apparatus **100**.

Accordingly, during operation, the electrode housing **708** is at the same electrical potential as the second electrode **110**, and both are connected to the positive terminal of the power supply. In this embodiment, this positive terminal voltage may range up to +300 volts. Since the electrode housing **708** is exposed in the present embodiment, the apparatus **100** is structurally configured to maintain a minimum separation gap in excess of several millimeters between the electrode housing and a grounded cylindrical pipe in which the apparatus **100** may be inserted, so that the ambient atmosphere in the gap sufficiently insulates the electrode housing from the pipe against this modest electrical potential difference between the two structures. Alternatively, the positive terminal voltage may be grounded, as disclosed in the above-noted U.S. Pat. No. 7,781,947.

In this embodiment, the electrode housing **708** further includes a liquid coolant inlet **712** shown in FIG. **7**, which receives liquid coolant from the cooling system **118**. The liquid coolant is channeled into the second electrode **110** through a cooling channel **714** shown in FIG. **8**, which directs the liquid coolant into the anode to cool it. The liquid coolant circulates through the second electrode **110** then exits the second electrode **110** into the exhaust chamber **704** and exhaust tube **702**, through which it exits the apparatus **100** along with the liquid and gas exiting the envelope **102**. The circulation of the coolant through the second electrode is described in the above-noted commonly owned U.S. Pat. No. 7,781,947, and therefore, further details are omitted herein.

Referring to FIGS. **2**, **7** and **8**, in this embodiment, the electrode housing **708** is connected to the second insulative housing **120**, with an O-ring sealing the connection therebetween. In this embodiment, the O-ring **716** is a silicone O-ring.

In this embodiment, the apparatus **100** includes a heat-resistant O-ring seal configured to seal at least one component of the apparatus **100** against the envelope. More particularly, in this embodiment the second insulative housing **120** includes two heat-resistant O-ring seals **720**, which in this embodiment are KALREZ™ perfluoroelastomer O-ring seals manufactured by DuPont, for sealing an inner surface of the second insulative housing **120** against an outer surface of the envelope **102**.

Referring to FIGS. **2**, **6**, **7** and **8**, in this embodiment the anode assembly **700** includes various components of the second shielding system **122**. More particularly, in this embodiment the shielding system **122** includes a light-piping shielding component **724** configured to prevent the electromagnetic radiation from axially exiting from an annular interior volume of the envelope **102**. More particularly still, in this embodiment the light-piping shielding component **724** includes an opaque washer abutting a distal end of the envelope. In this embodiment, the opaque washer is composed of brass. Thus, to the extent that some of the electromagnetic radiation emitted by the arc may travel axially outward within the annular interior volume of the envelope **102**, the light-piping shielding component **724** blocks such radiation from axially exiting the distal end of the envelope **102**, thereby preventing such radiation from striking or entering into the second insulative housing **120**.

Similarly, in this embodiment the inner surfaces of the second insulative housing **120** are also shielded against arc radiation travelling radially outward, by two additional components of the shielding system **122** described below.

Referring to FIGS. **2**, **7** and **8**, in this embodiment the second shielding system **122** includes a conductive shielding component **730** having an opaque surface. More particularly, in this embodiment the conductive shielding component **730** includes a sleeve which is inserted into an axially innermost end of the second insulative housing **120**. In this embodiment the sleeve is composed of copper, which is opaque, and therefore all of its surfaces are opaque.

Referring to FIGS. **2**, **6**, **7** and **8**, in this embodiment the shielding system **122** further includes an opaque portion **740** of the envelope **102**, as shown in FIG. **6**. More particularly, in this embodiment the opaque portion **740** of the envelope includes a portion of the envelope having an opaque coating **742** on an inside surface thereof. In the present embodiment, the opaque coating **742** is an HRC™ Heraeus Reflective Coating, as described earlier in connection with the similar cathode side opaque coating **462**. In this embodiment, the opaque coating **742** is applied over the axially outermost 80 mm of the inner surface of the envelope **102** at the anode side. In this embodiment, the envelope **102** has a thickness of about 3 mm at the anode side, and the opaque coating has a thickness of about 0.5 to 1 mm.

Referring to FIGS. **2**, **6** and **8**, in this embodiment the second shielding system **122** is further configured to block the electromagnetic radiation from striking an O-ring seal. More particularly, in this embodiment the opaque portion **740** of the envelope blocks the electromagnetic radiation emitted from the arc from striking the heat-resistant O-rings **720**.

Thus, as shown in FIG. **2**, in this embodiment the second shielding system **122**, or more particularly, the light-piping shielding component **724**, the opaque surface of the conductive shielding component **730** and the opaque portion **740** of the envelope **102**, block the electromagnetic radiation emitted by the arc **112** from striking all inner surfaces of the second insulative housing **120**. In the present embodiment, all three of these components of the shielding system **122** are advantageously cooled by the cooling system **118**, as discussed below.

Reflector Assembly

Referring back to FIGS. **1**, **2** and **3**, in this embodiment the apparatus **100** includes a reflector assembly shown generally at **150**. In this embodiment, the reflector assembly **150** includes a reflector **152**. More particularly, in this embodiment the reflector **152** is an elliptical reflector, configured to direct electromagnetic radiation emitted by the plasma arc **112** through the envelope **102** through a rectangular opening (not shown) defined at the bottom of the reflector **152**. In this embodiment, the reflector **152** has a polished copper body, and its elliptical reflective surface is a rhodium surface. More particularly, to form the reflective rhodium surface, the elliptical inner surface of the reflector **152** is coated first with electroless nickel then with high leveling bright nickel then with gold then with rhodium.

Referring to FIGS. **1**, **2** and **3**, in this embodiment, the reflector assembly **150** further includes a cathode assembly support plate **154** for connecting the reflector assembly **150** to the cathode assembly **400**, and an anode assembly support plate **156** for connecting the reflector assembly **150** to the anode assembly **700**. In this embodiment, the cathode assembly support plate **154** and the anode assembly support plate **156** are composed of copper.

Referring to FIGS. **2**, **3** and **4**, in this embodiment the cathode assembly support plate **154** abuts the conductive shielding component **450**, and is secured to the cathode assembly **400** by a plurality of bolts which extend through the axially innermost piece **114***b* of the insulative housing, through the conductive shielding component **450**, and into the body of the cathode assembly support plate **154**.

Similarly, referring to FIGS. **2** and **7**, in this embodiment the anode assembly support plate **156** abuts the conductive shielding component **730**, and is secured to the anode assembly **700** by a plurality of bolts which extend through the axially innermost end of the second insulative housing **120**, through the conductive shielding component **730** and into the body of the anode assembly support plate **156**.

In the present embodiment, the three main components of the reflector assembly **150**, namely, the reflector **152**, the cathode assembly support plate **154** and the anode assembly support plate **156**, all have internal coolant channels such as those shown at **158**, **160** and **162** for example, through which liquid coolant is directed, as discussed below.

Cooling System

Referring to FIGS. **1**, **2**, **3**, **9** and **10**, the cooling system is shown generally at **118** in FIG. **2**. Generally, in this embodiment, the cooling system **118** cools the various components of the shielding system **116** and the second shielding system **122**.

In this embodiment, the cooling system **118** includes an upper manifold **902** and a lower manifold **904** shown in FIGS. **9** and **10**. In the present embodiment, the lower manifold **904** is mounted on top of and attached to the reflector assembly **150**, and the upper manifold **902** is mounted on top of and attached to the lower manifold **904**.

In the present embodiment, the upper manifold **902** and lower manifold **904** are configured such that the anode side of the apparatus **100** is used for all external fluid connections to enable the apparatus **100** to receive supplies of liquids or gas from a fluid supply source system (not shown), and the cathode side of the apparatus is used only for fluid connections between different parts of the apparatus and not for external fluid connections. It will be recalled that the insulated bus connector **422** for the electrical connection to the cathode and the similar bus connector for electrical connection to the anode both have connection ports which point toward the anode side of the apparatus **100**. Thus, this configuration of fluid connections and electrical connections advantageously results in a compact design of the apparatus **100**, with all external connections being made from the anode side, which facilitates insertion of the apparatus **100** into cramped environments, such as the interior of an 8-inch diameter pipe for cladding applications, for example.

In this embodiment, the upper manifold **902** includes a main liquid coolant inlet port **906** at the anode side of the manifold, for receiving a liquid coolant from an external source (not shown). In this embodiment, the liquid coolant is de-ionized water. In the present embodiment, the upper manifold **902** divides the received flow of liquid coolant between a cathode supply outlet port **1002** at the cathode side of the upper manifold **902** and an anode supply outlet port **908** at the anode side of the upper manifold **902**.

In this embodiment, the cathode supply outlet port **1002** directs the liquid coolant to the liquid coolant inlet port **410** at the cathode supply plate **402**. As discussed earlier herein, in this embodiment the liquid coolant received at the liquid coolant inlet port **410** is supplied to the vortex generator **104** to generate the vortexing flow of liquid **106**, and to the first electrode **108** to circulate through the electrode and cool it, as discussed earlier herein. The vortexing flow of liquid **106** exits the apparatus **100** through the exhaust chamber **704** and exhaust tube **702**. The coolant supplied to the first electrode **108** circulates through the hot cathode then exits the cathode assembly **400** through the liquid coolant outlet port **412**, then re-enters the upper manifold **902** at a liquid coolant return inlet port **1004** and travels through the upper manifold **902** to a coolant outlet port **910**, through which the used coolant exits the apparatus **100**.

In this embodiment, the anode supply outlet port **908** directs liquid coolant to the liquid coolant inlet **712** of the electrode housing **708** of the anode assembly **700**. The liquid coolant received at the inlet **712** is circulated through the cooling channel **714** and through the second electrode **110**, and is then exhausted through the exhaust chamber **704** and exhaust tube **702** along with the vortexing flows of liquid **106** and gas that have passed through the envelope **102**, as discussed earlier herein.

In the present embodiment, the upper manifold **902** further includes a purge gas supply inlet **912**, through which a pressurized purge gas is supplied to maintain a pressurized flow of inert gas around the outside of the envelope **102**. In this embodiment, the pressurized purge gas is argon, and the upper manifold **902** directs the received purge gas through a plurality of holes (not shown) defined through the reflector **152** of the reflector assembly **150**. For some applications, such a flow of purge gas may reduce the likelihood of external environmental particulate contamination of the outside surfaces of the envelope **102** and the reflector **152**.

In this embodiment, the lower manifold **904** includes a reflector coolant supply inlet port **920**, for receiving a pressurized flow of liquid coolant from an external source (not shown) and for supplying the liquid coolant to the reflector assembly **150**. In this embodiment, the coolant is facility cooling water, and the lower manifold **904** directs the water received at the inlet port **920** through the reflector assembly **150**. More particularly, in this embodiment the lower manifold **904** directs the received coolant to circulate through the internal cooling channels such as those shown at **158**, **160** and **162**, of the reflector **152**, the cathode assembly support plate **154** and the anode assembly support plate **156**.

In the present embodiment, the lower manifold **904** further includes a reflector coolant return outlet port **922**. In this embodiment, when the pressurized liquid coolant has circulated through the internal cooling channels of the reflector assembly **150** as described above, the lower manifold **904** then directs the liquid coolant to exit the apparatus **100** through the reflector coolant return outlet port **922**.

In this embodiment, the lower manifold **904** further includes a first inert gas supply inlet port **924**, a second inert gas supply inlet port **926**, a first inert gas supply outlet port **1020** and a second inert gas supply outlet port **1022**.

In the present embodiment, the first inert gas supply inlet port **924** receives a pressurized supply of inert gas, which in this embodiment is argon. The pressurized argon exits the lower manifold **904** at the first inert gas supply outlet port **1020**, which is connected to the inert gas supply inlet port **414**. The inert gas supply inlet port **414** supplies the pressurized flow of argon to the vortex generator **104**, to generate a vortexing flow of argon radially inward from the vortexing flow of liquid **106**, as discussed earlier herein.

In this embodiment, the second inert gas supply inlet port **926** receives a pressurized supply of inert gas, which in this embodiment is nitrogen. The pressurized nitrogen exits the lower manifold **904** at the second inert gas supply outlet port **1022**, which is connected to the insulative gas supply inlet port **430**, to fill and pressurize the thin gap **432** shown in FIG. **3** between the insulative housing **114** and the insulative shielding component **440**, as discussed above.

Referring to FIGS. **1** and **9**, in this embodiment the cooling system **118** further includes a liquid and gas return outlet port **950**, connected to and axially outward from the liquid and gas exhaust tube **702**, through which the vortexing flow of liquid **106**, its accompanying vortexing flow of inert gas, and coolant from the second electrode **110**, exit the apparatus **100**.

Referring to FIG. **2**, in this embodiment the cooling system **118** also includes certain components of the cathode assembly **400**, notably including the vortex generator **104**, as well as certain components of the reflector assembly **150**, notably including the cathode assembly support plate **154** and the anode assembly support plate **156**, as discussed in greater detail below.

Operation

During operation, although most of the electromagnetic radiation emitted by the plasma arc **112** travels radially outward through the envelope **102** and exits the apparatus **100**, a small percentage of the electromagnetic radiation emitted by the arc tends to travel axially outward within the apparatus **100**, past the tips of the first and second electrodes **108** and **110**, where it becomes incident upon internal components of the apparatus **100**. Although this internal irradiance would not tend to be problematic for short durations at very high power levels, or for longer durations at lower power levels, such internal irradiance may have significant heating effects if the apparatus **100** is operated continuously at extreme power levels of hundreds of kilowatts for longer durations, ranging from minutes to several hours of continuous operation for some cladding applications, for example. Without the shielding and cooling of the present embodiment, such heating may be problematic for insulative components of the apparatus **100** such as the insulative housings **114** and **120**, as discussed earlier herein.

Referring back to FIGS. **2**, **3**, **6**, **9** and **10**, as discussed earlier herein, in this embodiment the shielding system **116** is advantageously configured to block electromagnetic radiation emitted by the arc **112** to prevent the electromagnetic radiation from striking all inner surfaces of the insulative housing **114**. More particularly, in this embodiment the opaque surface of the insulative shielding component **440**, the opaque portion **460** of the envelope **102** and the opaque surface of the conductive shielding component **450**, block the electromagnetic radiation emitted by the arc **112** from striking all inner surfaces of the insulative housing **114**. Advantageously, therefore, in this embodiment the shielding system **116** prevents internal electromagnetic radiation within the apparatus **100** from striking the insulative housing **114**, thereby preventing such radiation from being directly absorbed by the housing and melting it, and also preventing such internal radiation from travelling through the housing to overheat adjacent components of the apparatus which could then melt the adjacent surfaces of the housing.

However, in the absence of additional cooling of the shielding system, additional problems may arise. For example, if the internal arc radiation delivers too much heat energy to the inner opaque surface of the insulative shielding component **440**, which in this embodiment is ceramic, the irradiated inner opaque surface may become much hotter than the body or bulk of the ceramic material, causing large thermal gradients and stresses in the ceramic material, which may crack then ultimately fracture the ceramic material. Similarly, if the arc radiation delivers too much heat energy to the inner surface of the conductive shielding component **450**, which in this embodiment is copper, the entire mass of the conductive shielding component **450** may overheat, potentially melting the adjacent surface of the insulative housing **114**. Finally, if the arc radiation delivers too much heat energy to the opaque portion **460** of the envelope **102**, the opaque portion may eventually overheat and begin to emit significant amounts of infrared radiation. Advantageously, therefore, in this embodiment the cooling system **118** avoids these problems by cooling the shielding system **116**.

In this embodiment, the cooling system **118** includes the vortex generator **104**, and the vortex generator **104** is configured to expose the opaque surface of the insulative shielding component **440** to the vortexing flow of liquid **106**. As shown in FIG. **3**, the vortexing flow of liquid **106** is in direct contact with the radially innermost surface of the insulative shielding component **440**. Due to the high volumetric flow rate of the vortexing flow of liquid **106**, the vortexing flow of liquid **106** can remove heat energy from the opaque surface at a rate much faster than the rate at which heat energy can be delivered to the opaque surface by the internal arc radiation. Advantageously, the surface of the insulative shielding component that is exposed to the vortexing flow of liquid **106** is the same opaque surface that blocks the electromagnetic radiation emitted by the arc and prevents it from striking the inner surface of the insulative housing **114**. Therefore, the same opaque surface that blocks and absorbs some of the internal arc radiation is cooled by the vortexing flow of liquid **106** which prevents overheating of the opaque surface. Accordingly, thermal gradients and thermal stresses within the insulative shielding component **440** are minimized, thereby avoiding the problems of potential cracking and fracturing of the ceramic material of the insulative shielding component **440** that may otherwise have arisen from differential heating of the opaque surface of the insulative shielding component relative to its bulk.

Still referring to FIG. **3**, in this embodiment the vortex generator **104** is also configured to expose the opaque portion **460** of the envelope **102** and the light-piping shielding component **480** to the vortexing flow of liquid **106**. Advantageously, therefore, despite its role in blocking electromagnetic radiation emitted by the arc, the opaque portion **460** of the envelope **102** and the light-piping shielding component **480** do not overheat and do not begin to excessively emit infrared radiation.

In this embodiment, unlike the opaque surface of the insulative shielding component **440** and the opaque portion **460** of the envelope **102**, in this embodiment the conductive shielding component **450** is not in direct contact with the vortexing flow of liquid **106**. Rather, in this embodiment, the cooling system **118** is configured to conductively cool the conductive shielding component **450**.

In this regard, in the present embodiment, the cooling system **118** includes a liquid cooled conductor in conductive contact with the conductive shielding component **450**. More particularly, in this embodiment the liquid cooled conductor is the cathode assembly support plate **154** of the reflector assembly **150**. It will be recalled that in this embodiment, the cathode assembly support plate **154** has internal cooling channels such as that shown at **158**, through which liquid coolant is circulated. As shown in FIG. **3**, in this embodiment the conductive shielding component **450** is in direct conductive contact with the liquid cooled cathode assembly support plate **154**. Accordingly, to the extent that internal arc radiation tends to heat the conductive shielding component **450**, such heat energy is conducted into the cathode assembly support plate **154** and is then removed by the circulating flow of liquid coolant therethrough.

In this embodiment, components of the second shielding system **122** at the anode side of the apparatus **100** are similarly cooled by the cooling system **118**.

For example, referring to FIGS. **2** and **6**, in this embodiment the vortex generator **104** is configured to expose both the opaque portion **740** of the envelope **102** and the light-piping shielding component **724** to the vortexing flow of liquid **106**, thereby cooling these two shielding components and preventing internal arc radiation from overheating them.

Referring to FIGS. **2** and **7**, in this embodiment the cooling system **118** includes a liquid cooled conductor in conductive contact with the conductive shielding component **730**. More particularly, in this embodiment the liquid cooled conductor is the anode assembly support plate **156** of the reflector assembly **150**, which has internal cooling channels such as that shown at **162** through which liquid coolant is circulated. As shown in FIG. **2**, in this embodiment the conductive shielding component **730** is in direct conductive contact with the liquid cooled anode assembly support plate **156**. Accordingly, to the extent that internal arc radiation tends to heat the conductive shielding component **730**, such heat energy is conducted into the anode assembly support plate **156** and is then removed by the circulating flow of liquid coolant therethrough.

Alternatives

Referring to FIGS. **2**, **6** and **11**, an envelope according to a second embodiment of the disclosure is shown generally at **1100** in FIG. **11**. In this embodiment, the shielding system **116** and the shielding system **122** are modified by replacing the envelope **102** shown in FIG. **6** with the envelope **1100** shown in FIG. **11**. In this embodiment, the shielding system **116** includes an opaque portion of the envelope **1100**, namely, a cathode side opaque portion **1104**, and similarly, the shielding system **122** includes another opaque portion of the envelope **1100**, namely, an anode side opaque portion **1106**.

In this embodiment, the envelope **1100** also includes a central portion **1102**, which is composed of the same material as the envelope **102** shown in FIG. **6**, namely, HSQ **300** grade electrically fused quartz manufactured by Heraeus.

However, in this embodiment the opaque portions **1104** and **1106** are composed of opaque quartz. More particularly, in this embodiment the opaque portions **1104** and **1106** are composed of OM **100** opaque quartz glass manufactured by Heraeus. This material includes small, irregularly shaped micron-sized pores which are evenly distributed in an amorphous opaque quartz matrix, resulting in efficient diffuse scattering of electromagnetic radiation. In this embodiment, the opaque portion **1104** consists of the axially outermost 55 mm of the envelope **1100** at the cathode side, and the opaque portion **1106** consists of the axially outermost 80 mm of the envelope **1100** at the anode side. In the present embodiment, as with the previous embodiment, the lengths of the opaque portions are selected to be sufficiently long to block internal arc radiation from striking internal shielding components as described above, but sufficiently short that they do not extend inwardly past the tips of the electrodes, thus avoiding any inadvertent blocking of radiation which would otherwise exit the apparatus **100** through the reflector assembly **150**. In this embodiment, the central portion **1102** is joined to the opaque portions **1104** and **1106** by carefully melting them together while striving to maintain concentricity, surface smoothness and dimensional accuracy to the greatest extent possible.

In this embodiment, the opaque portions **1104** and **1106** are advantageously cooled by the cooling system **118**, or more particularly by the vortexing flow of liquid **106** which is generated by the vortex generator **104** of the cooling system **118**, in the same manner as the opaque portions **460** and **740** of the previous embodiment.

Referring to FIGS. **1**, **9**, **10** and **12**, an apparatus for generating electromagnetic radiation according to a third embodiment of the invention is shown generally at **1200** in FIG. **12**. In this embodiment, the apparatus **1200** is identical to the apparatus **100** shown in FIG. **1**, except in respect of the variations discussed below.

In this embodiment, the apparatus **1200** further includes an external heat shield **1202** configured to heat-shield at least some of an outer surface of the insulative housing **114**, and the cooling system **118** is further configured to cool the external heat shield **1202**.

In this embodiment, the external heat shield **1202** is a conductor. More particularly, in this embodiment the external heat shield **1202** is composed of anodized aluminum, and has liquid coolant channels (not shown) extending through its interior volume.

Referring to FIGS. **9** and **10**, in this embodiment the lower manifold **904** of the cooling system further includes an external shield coolant supply outlet port **1204**, and the upper manifold **902** further includes an external shield coolant return inlet port **1206** and an external shield coolant return outlet port **1208**. The lower manifold receives a pressurized liquid coolant flow at the reflector coolant supply inlet port **920**, and diverts a portion of the pressurized liquid coolant to the external shield coolant supply outlet port **1204**, which is connected via a copper tube (not shown) to a coolant supply inlet port (not shown) of the external heat shield **1202**. The liquid coolant circulates through the internal coolant channels inside the external heat shield **1202** then exits the external heat shield **1202** through a coolant return outlet port **1210** of the external heat shield **1202**. The coolant return outlet port **1210** is connected via a copper tube (not shown) to the external shield coolant return inlet port **1206** of the upper manifold **902**, through which the used liquid coolant flows through the upper manifold **902** then exits from the apparatus **1200** via the external shield coolant return outlet port **1208**.

The liquid-cooled external heat shield **1202** may be advantageous for some particular applications. For example, if the apparatus **1200** is being used for cladding, to metallurgically bond a coating to the interior surface of a pipe, the apparatus **1200** may be inserted fully into the pipe with the cathode assembly **400** protruding from the far end of the pipe and the reflector assembly **150** aligned over the inner surface of the pipe at the far end. The coated pipe may then be rotated while the apparatus **1200** is gradually pulled longitudinally back through the pipe, so that the reflector **152** scans the electromagnetic radiation emitted by the arc across the interior surface of the pipe in a spiraling fashion. In such an application, the portion of the pipe presently facing the cathode assembly **400** tends to be hot, as that portion of the pipe was very recently exposed to the high-intensity electromagnetic radiation emitted from the reflector **152**. Accordingly, the liquid cooled external heat shield **1202** shields the cathode assembly from heat transfer through conduction, convection and radiation which would otherwise occur in the ambient environment of the pipe. In this embodiment, the external heat shield **1202** also shields the exterior of the insulative housing **114** from electromagnetic radiation emitted by the arc that may be scattered or reflected by the pipe, and shields the cathode assembly **400** from debris coming from the heated pipe.

Alternatively, or in addition, a similar external heat shield (not shown) may be provided at the anode side of the apparatus **1200**.

While specific embodiments have been described and illustrated, such embodiments should be considered illustrative only and not as limiting the invention as defined by the accompanying claims.

What is claimed is:

1. An apparatus for generating electromagnetic radiation, the apparatus comprising:

a) an envelope;

b) a vortex generator configured to generate a vortexing flow of liquid along an inside surface of the envelope;

c) first and second electrodes within the envelope configured to generate a plasma arc therebetween;

d) an insulative housing surrounding at least a portion of an electrical connection to one of the electrodes;

e) a shielding system configured to block electromagnetic radiation emitted by the arc to prevent the electromagnetic radiation from striking all inner surfaces of the insulative housing; and

f) a cooling system configured to cool the shielding system.

2. The apparatus of claim **1** wherein the shielding system comprises an insulative shielding component having an opaque surface configured to block the electromagnetic radiation.

3. The apparatus of claim **2** wherein the insulative shielding component comprises a ceramic shielding component.

4. The apparatus of claim **2** wherein the cooling system comprises the vortex generator and wherein the vortex generator is configured to expose the opaque surface of the insulative shielding component to the vortexing flow of liquid.

5. The apparatus of claim **1** wherein the shielding system comprises an opaque portion of the envelope configured to block the electromagnetic radiation.

6. The apparatus of claim **5** wherein the opaque portion of the envelope comprises a portion of the envelope having an opaque coating on an inside surface thereof.

7. The apparatus of claim **5** wherein the opaque portion of the envelope is composed of opaque quartz.

8. The apparatus of claim **5** wherein the cooling system comprises the vortex generator and wherein the vortex generator is configured to expose the opaque portion of the envelope to the vortexing flow of liquid.

9. The apparatus of claim **1** wherein the shielding system comprises a conductive shielding component having an opaque surface configured to block the electromagnetic radiation.

10. The apparatus of claim **9** wherein the cooling system is configured to conductively cool the conductive shielding component.

11. The apparatus of claim **10** wherein the cooling system comprises a liquid cooled conductor in conductive contact with the conductive shielding component.

12. The apparatus of claim **1** wherein the shielding system is further configured to block the electromagnetic radiation from striking an O-ring seal.

13. The apparatus of claim **1** further comprising a heat-resistant O-ring seal configured to seal at least one component of the apparatus against the envelope.

14. The apparatus of claim **1** further comprising a second insulative housing surrounding at least a portion of the other one of the electrodes, and a second shielding system configured to block the electromagnetic radiation emitted by the arc to prevent the electromagnetic radiation from striking all inner surfaces of the second insulative housing, wherein the cooling system is configured to cool the second shielding system.

15. The apparatus of claim **1** wherein the shielding system further comprises a light-piping shielding component configured to prevent the electromagnetic radiation from axially exiting from an annular interior volume of the envelope.

16. The apparatus of claim **15** wherein the light-piping shielding component comprises an opaque washer abutting a distal end of the envelope.

17. The apparatus of claim **15** wherein the cooling system comprises the vortex generator and wherein the vortex generator is configured to expose the light-piping shielding component to the vortexing flow of liquid.

18. The apparatus of claim **1**, further comprising an external heat shield configured to heat-shield at least some of an outer surface of the insulative housing, wherein the cooling system is further configured to cool the external heat shield.

19. An apparatus for generating electromagnetic radiation, the apparatus comprising:

a) means for generating a vortexing flow of liquid along an inside surface of an envelope;

b) means for generating a plasma arc between first and second electrodes within the envelope;

c) means for blocking electromagnetic radiation emitted by the arc to prevent the electromagnetic radiation from striking all inner surfaces of an insulative housing surrounding at least a portion of an electrical connection to one of the electrodes; and

d) means for cooling the means for blocking.

20. A method of generating electromagnetic radiation, the method comprising:

a) generating a vortexing flow of liquid along an inside surface of an envelope;

b) generating a plasma arc between first and second electrodes within the envelope;

c) blocking electromagnetic radiation emitted by the arc with a shielding system to prevent the electromagnetic radiation from striking all inner surfaces of an insulative housing surrounding at least a portion of an electrical connection to one of the electrodes; and

d) cooling the shielding system.

21. The method of claim **20** wherein blocking comprises blocking the electromagnetic radiation with an opaque surface of an insulative shielding component of the shielding system.

22. The method of claim **21** wherein the insulative shielding component comprises a ceramic shielding component.

23. The method of claim **21** wherein cooling comprises exposing the opaque surface of the insulative shielding component to the vortexing flow of liquid.

24. The method of claim **20** wherein blocking comprises blocking the electromagnetic radiation with an opaque portion of the envelope.

25. The method of claim **24** wherein the opaque portion of the envelope comprises a portion of the envelope having an opaque coating on an inside surface thereof.

26. The method of claim **24** wherein the opaque portion of the envelope is composed of opaque quartz.

27. The method of claim **24** wherein cooling comprises exposing the opaque portion of the envelope to the vortexing flow of liquid.

28. The method of claim **20** wherein blocking comprises blocking the electromagnetic radiation with an opaque surface of a conductive shielding component of the shielding system.

29. The method of claim **28** wherein cooling comprises conductively cooling the conductive shielding component.

30. The method of claim **29** wherein conductively cooling comprises conducting heat energy between the conductive shielding component and a liquid cooled conductor.

31. The method of claim **20** wherein blocking further comprises blocking the electromagnetic radiation from striking an O-ring seal.

32. The method of claim **20** further comprising sealing at least one component against the envelope with a heat-resistant O-ring seal.

33. The method of claim **20** further comprising blocking the electromagnetic radiation emitted by the arc with a second shielding system to prevent the electromagnetic radiation from striking all inner surfaces of a second insulative housing surrounding at least a portion of the other one of the electrodes, and cooling the second shielding system.

34. The method of claim **20** wherein blocking further comprises blocking the electromagnetic radiation with a light-piping shielding component of the shielding system to prevent the electromagnetic radiation from axially exiting from an annular interior volume of the envelope.

35. The method of claim **34** wherein the light-piping shielding component comprises an opaque washer abutting a distal end of the envelope.

36. The method of claim **34** wherein cooling comprises exposing the light-piping shielding component to the vortexing flow of liquid.

37. The method of claim **20** further comprising heat-shielding at least some of an outer surface of the insulative housing with an external heat shield, and cooling the external heat shield.

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